Precipitation Variability Across Satellite Field-of-Views (FOVs) Derived from Ground-Based Polarimetric Radar Observations

Christopher R. Williams[1,2] , Walter A. Petersen[3], David B. Wolff[4] and V. Chandrasekar[5]

[1]University of Colorado Boulder

[2]NOAA Earth System Research Laboratory (ESRL)

[3]NASA Marshall Space Flight Center (MSFC)

[4]NASA Wallops Flight Facility (WFF)

[5]Colorado State University

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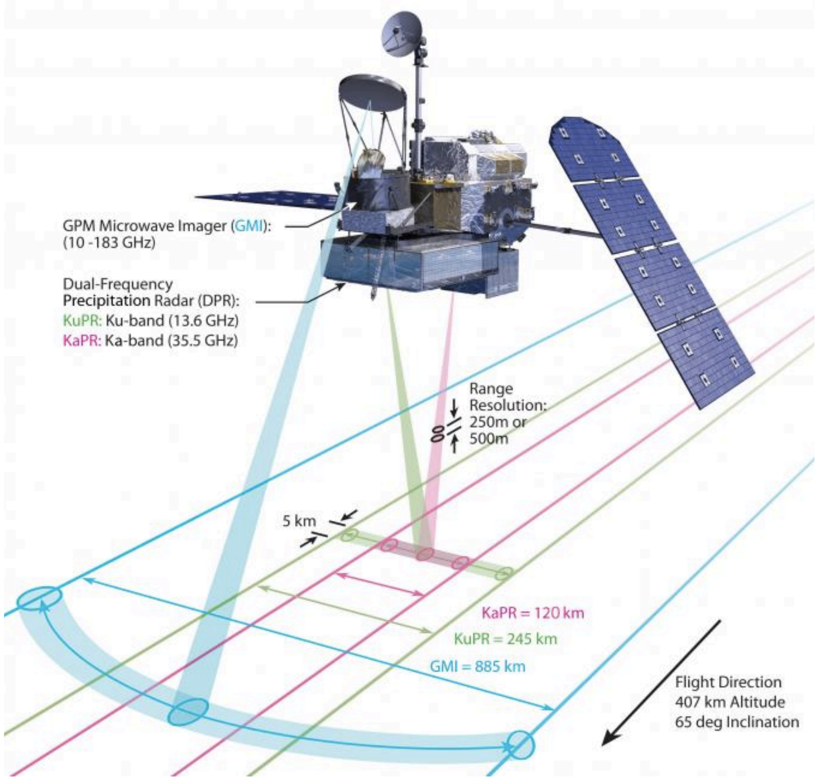
Motivation

- Typically, *assume* the radar pulse volume is uniformly filled with hydrometeors.
- This assumption breaks down as the radar pulse volume increases.

Questions:

- What is the precipitation variability across the 5 km GPM Dual-Frequency Precipitation Radar (DPR) footprint?
- To help rainfall retrieval algorithms, is there enough statistical signal to parameterize sub-volume variability using neighboring radar observations? (aka, downscaling)

NASA/JAXA Global Precipitation Measuring Mission (GPM) Core Observatory



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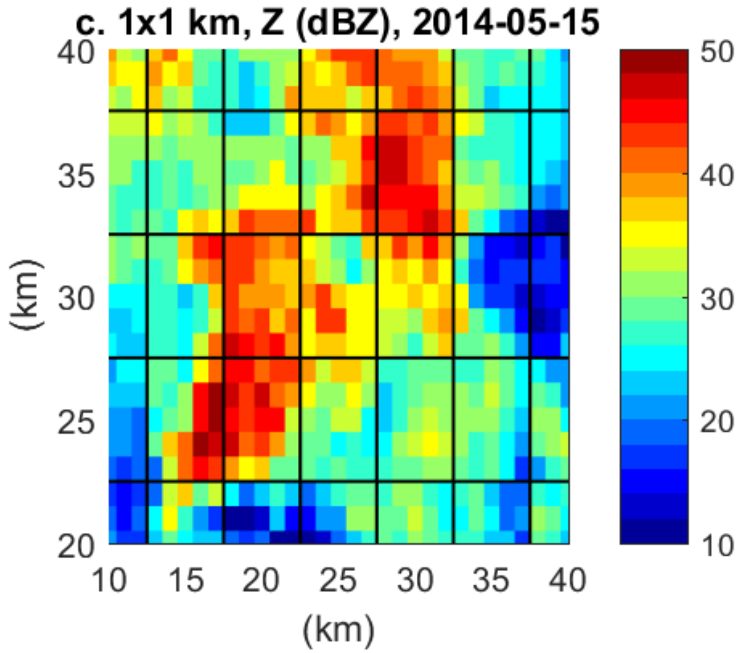
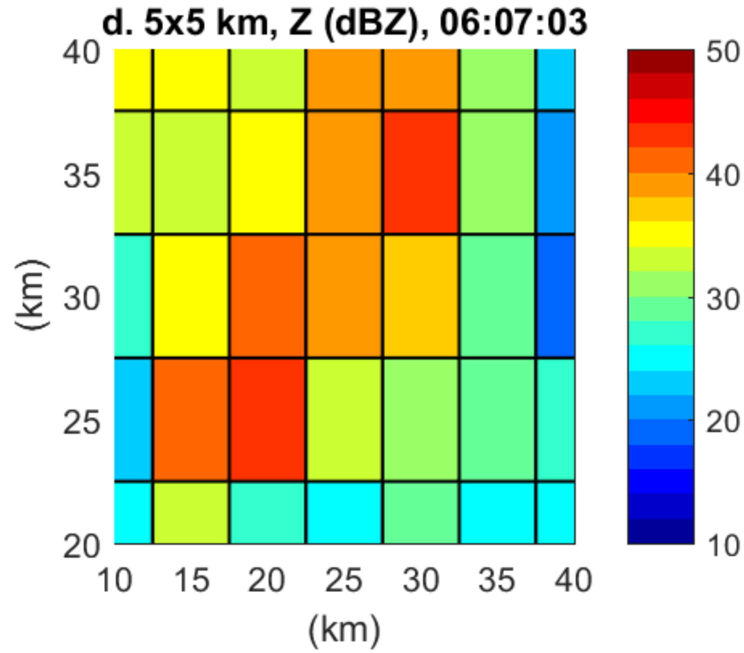
Precipitation Variability at different scales

High resolution NASA *Ground Validation* (GV) Program ground-based radar observations

Simulate larger volume satellite observations





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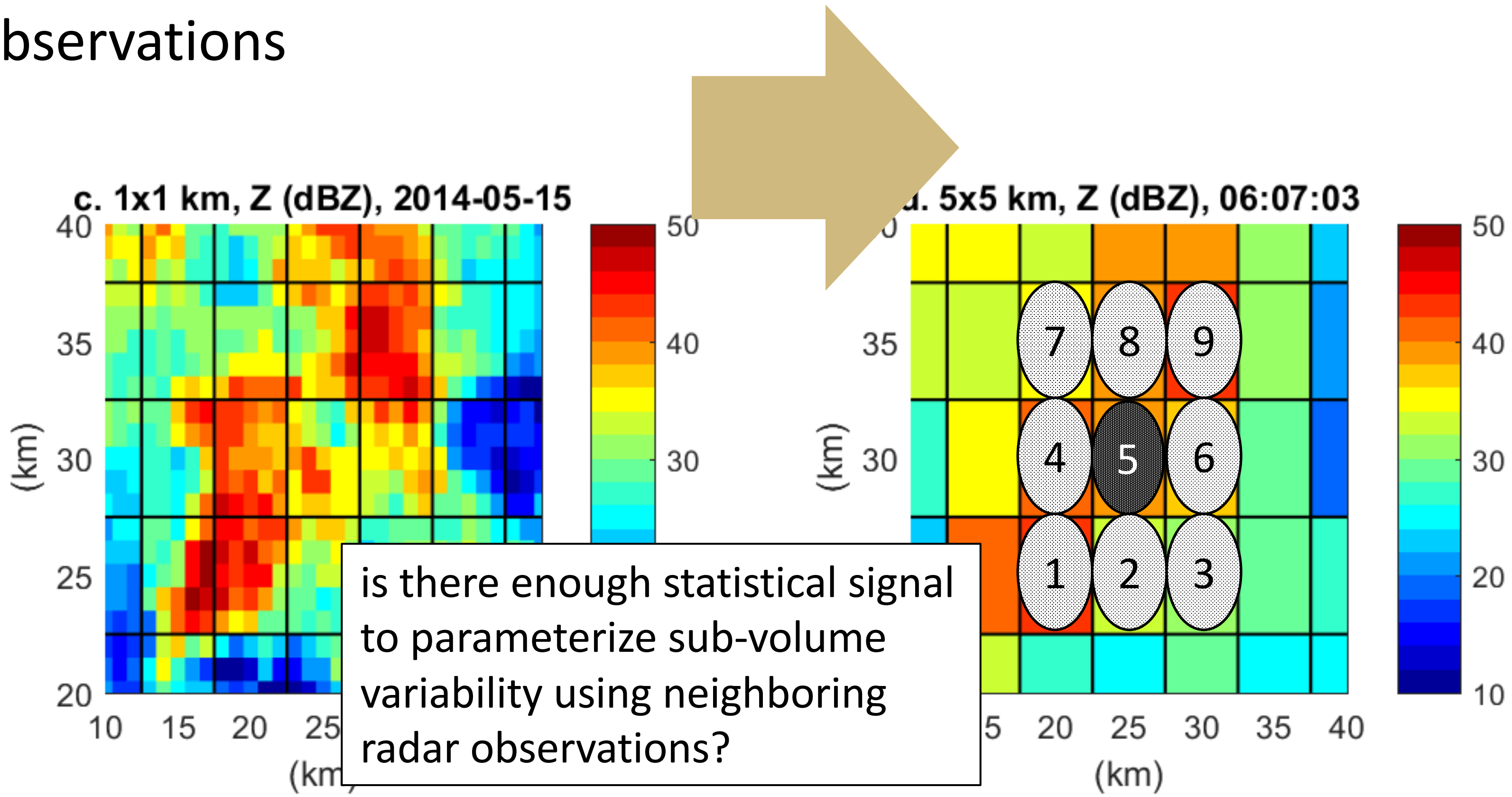


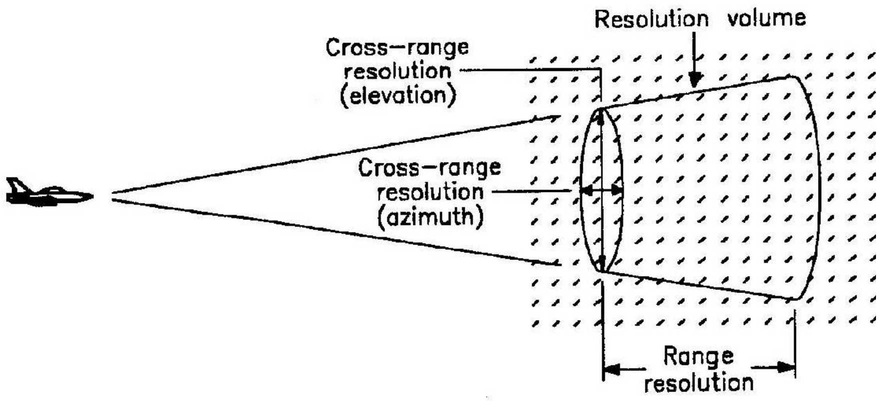
is there enough statistical signal to parameterize sub-volume variability using neighboring radar observations?

Outline of Presentation

- Definition of Terms
- Impacts of sub-FOV variability on satellite algorithms
- Power-law formulation in PR & DPR algorithms
- NASA Ground Validation (GV) Program Observations
  - Describe scanning radar data set
  - Simulate Ku/Ka-band reflectivity and specific attenuation
  - Simulate DPR Field of View (FOV)
- Statistics: FOV vs. 3x3 neighboring pixels
- Impacts of NUBF on PIA SRT estimates
- Concluding remarks and future work

Definition of Terms

- Instantaneous Field-of-View (IFOV or FOV)
  - Radar pulse volume weighted by
    - ***antenna pattern (cross-beam or spatial)***
    - ***receiver bandwidth (along-beam or range)***
- Non-Uniform Beam Filling (NUBF)
  - Precipitation variability within FOV



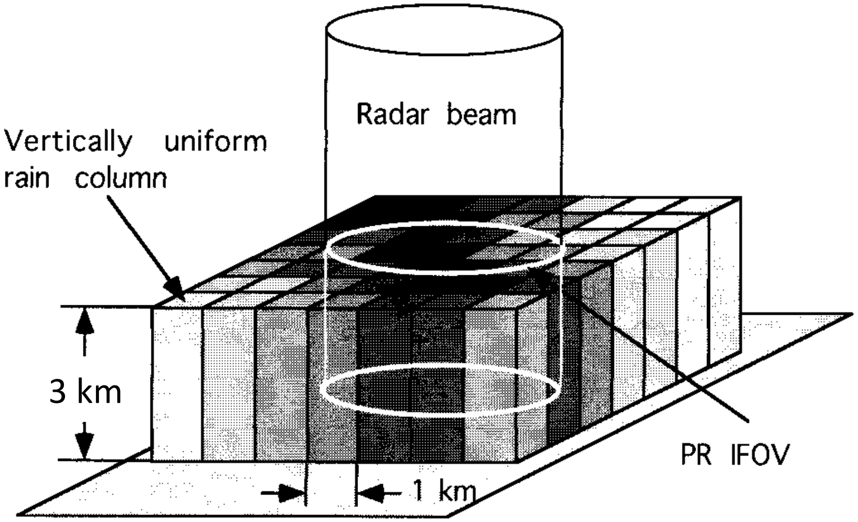


FIG. 1. Concept of storm model.

(Kozu & Iguchi 1999)

Impact of NUBF on Satellite Algorithms

- Impact #1: Area averaging of rain rate and reflectivity
  - From Jensen's equality, and concave functions ($b < 1$), averaged rain rate $< R >$ and averaged reflectivity $< Z >$:

$$\langle R \rangle = \left\langle aZ^b \right\rangle \leq a \langle Z \rangle^b$$

Magnitude of the inequality increases with spatial variability

- Impact #2: Path Integrated Attenuation (PIA) is underestimated
  - Narrow columns of large Z have larger path integrated attenuation which reduce measured Z at further ranges *in that column*
  - Area average specific attenuation k [dB/km] is not a simple relationship:

$$Z_m^{top} - Z_m^{bottom} \neq (2\Delta ht)k,$$

where Δht is the distance between the two measurements

Note that multiple scattering modifies Z_m and k in complex ways within the FOV. NUBF occurs before multiple scattering occurs (at 5 km scales). Thus, NUBF is a pre-condition for multiple scattering (Battaglia et al. 2015)

PR & DPR Algorithm Formulation

- Power law relationships:

  $k - \mathcal{Z}$ $\quad k = \alpha \mathcal{Z}^{\beta}$ $\quad [k]$ = [dB/km], $[\mathcal{Z}]$ = [mm^6/m^3]

  $R - \mathcal{Z}$ $\quad R = a \mathcal{Z}^{b}$ $\quad [R]$ = [mm/hr]

- Solver module based on Hitschfeld-Bordan method (Iguchi & Meneghini 1994; Iguchi et al. 2000)

  $$k = \varepsilon\, \alpha \mathcal{Z}^{\beta}$$

  $$R = \varepsilon' a \mathcal{Z}^{b}$$

- Solver module adjusts ε until convergence
  - DSD adjustment
  - NUBF adjustment (larger of the two adjustments)

Quantifying NUBF Variability

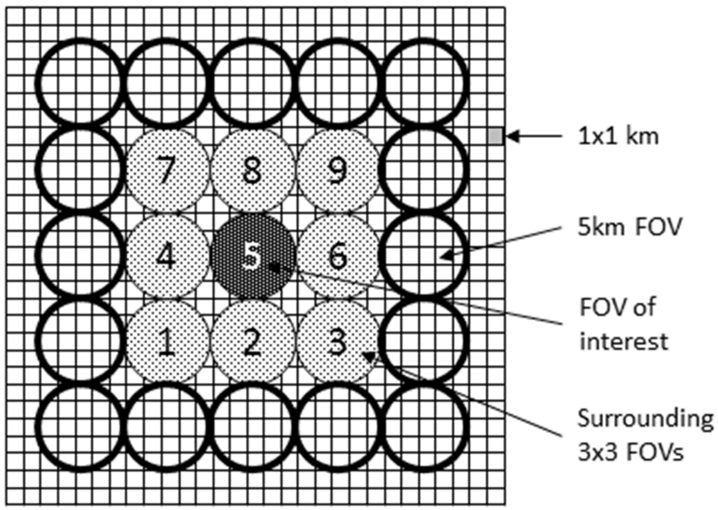
- Kozu & Iguchi (1999) used tropical TOGA-COARE scanning radar observations to relate field-of-view (FOV) variability with variability of surrounding FOV mean values.
- Two-pass algorithms:
  - First pass provides estimates of neighboring FOVs that are used to parameterize sub-FOV variability
  - Second pass includes NUBF parameterization
- NUBF variability parameterized using *coefficient of variation* (cov)

  cov = standard deviation / mean

  - Notation:

    "FOV cov" = sub-FOV variability

    "3x3 cov" = neighborhood variability



Question:
Are there relationships between FOV cov and 3x3 cov in naturally occurring rain?

Ground Based Radar Observations

- NASA Global Precipitation Measurement (GPM) satellite sponsored Ground Validation (GV) field campaign
- Integrated Precipitation and Hydrology Experiment (IPHEx)
- Southern Appalachian Mountains (North & South Carolina, USA)
- May-June 2014

PPI Scan Strategy

3 elevation angles (1.5°, 2° and 3°)
360° azimuth rotation (6°/s)
Maximum range 150 km
Limit data to 60 km: height is ~1.75 km AGL
1° beam width (~1 km breadth @ 60 km
125 m range resolution

This analysis used:

3° PPI scan
3 minute temporal resolution

NASA S-band Polarimeteric Radar (NPOL)

Converting Raw Data into 1x1 km Grid

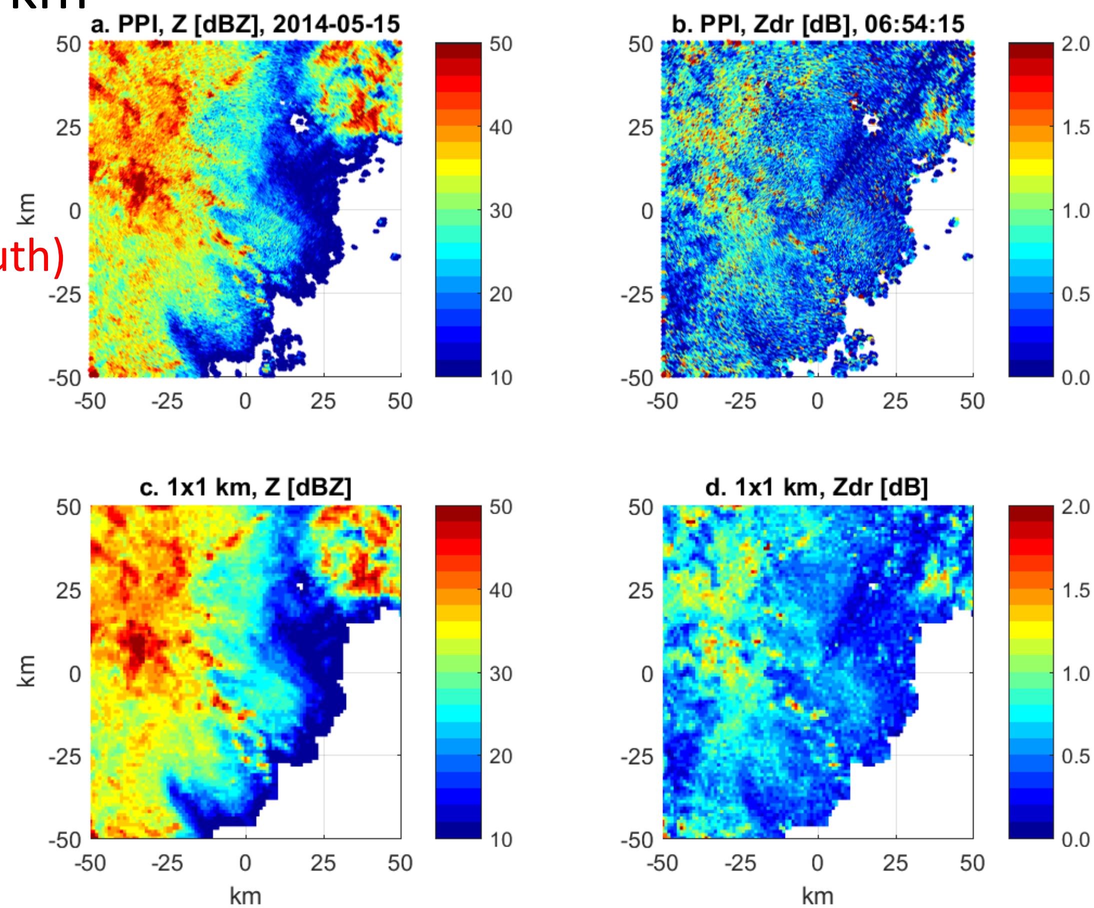
- Polarimetric samples in cylindrical coordinate:
  - Reflectivity: Z_h [dBZ]
  - Differential Reflectivity: Z_{dr} [dB]
- Grid PPI scans to 1x1 km
  - Gaussian weight
  - 6 dB loss at 1 km

Reflectivity

Differential Reflectivity

Raw Observations (range, azimuth)

1x1 km grid



DSD Parameters (1x1 km)

- Modified Gamma shape raindrop size distribution:

$$N(D) = N_w \left[\frac{6}{4^4}\frac{(\mu+4)^{\mu+4}}{\Gamma(\mu+4)}\right]\left(\frac{D}{D_m}\right)^{\mu} exp\left[-(\mu+4)\left(\frac{D}{D_m}\right)\right]$$

With parameters

N_w – Normalized number concentration [#/mm/m^3]

D_m – Mean volume-weighted diameter [mm]

μ – Shape parameter

- Comparisons with IPHEx disdrometers, GV found relationships:

$D_m = 0.1887Z_{dr}^3 - 1.0024Z_{dr}^2 + 2.3153Z_{dr} + 0.3834$

$N_w = 35.43\left[10^{(Z_h/10)}\right]D_m^{-7.192}$

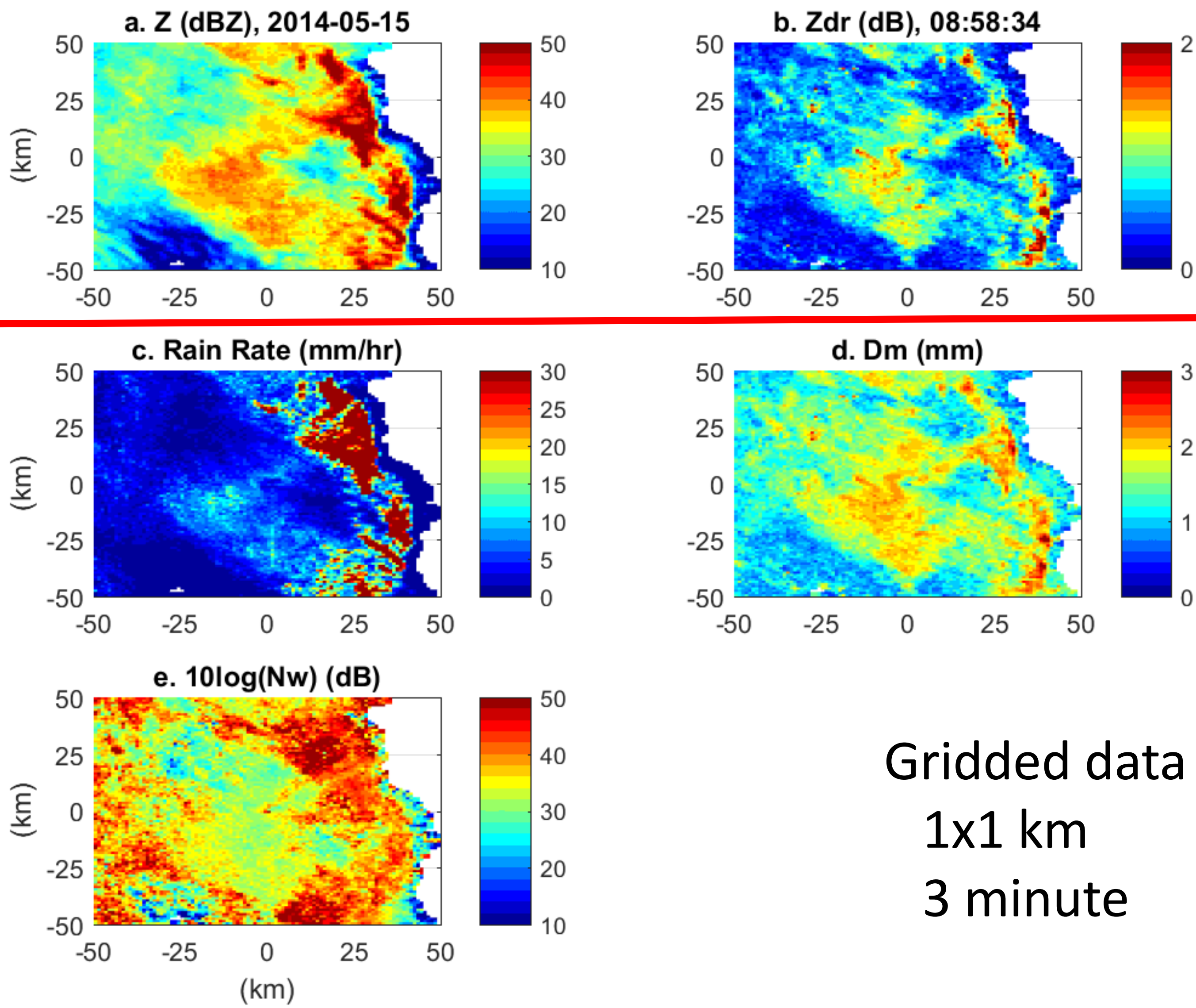
- Shape parameter assumed dependent on D_m (Williams et al. 2014)

$\mu = \frac{D_m^{0.72}}{0.09} - 4$

- Estimate rain rate

$$R = \frac{6\pi}{10^4}\sum_{D=0}^{D_{max}} N(D)D^3\, v(D)\Delta D$$

DSD Parameters & Rain Rate (1x1 km)



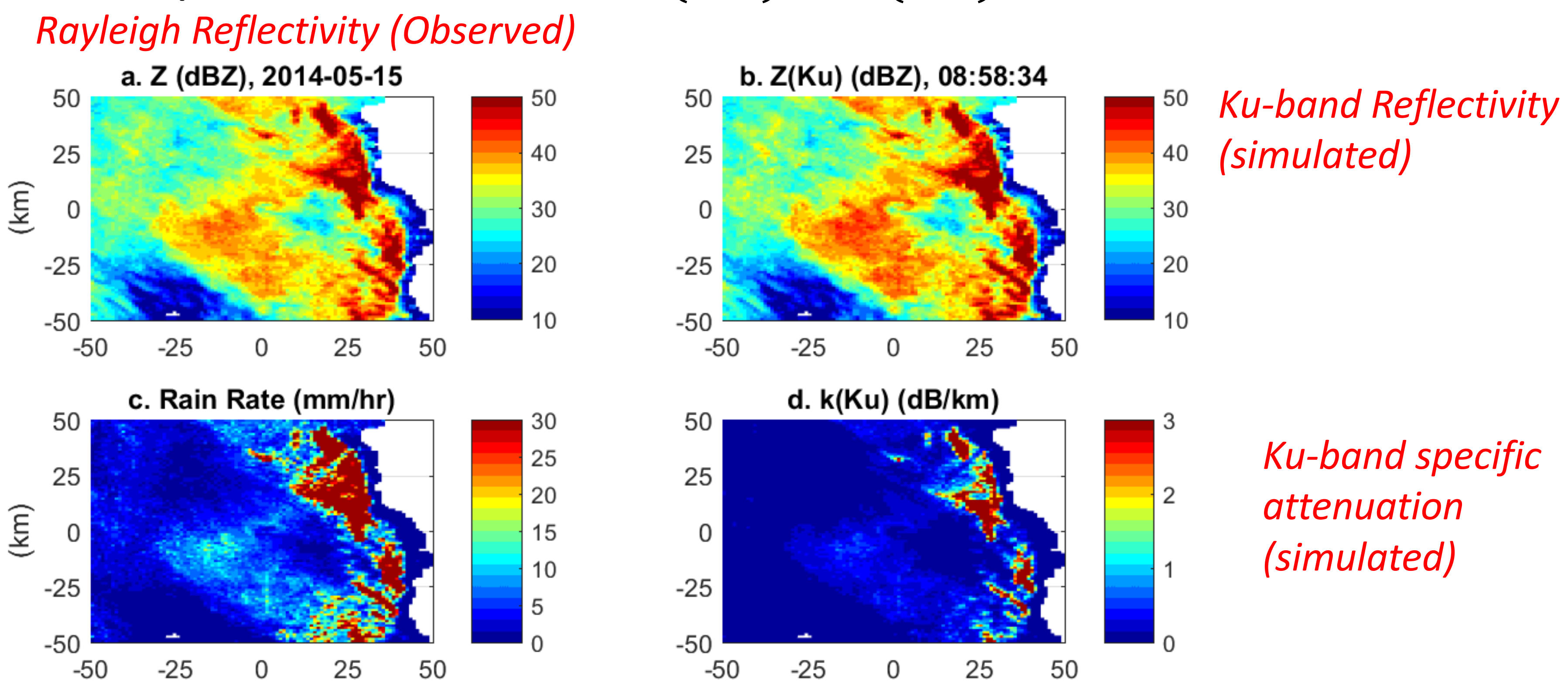
Inputs
Z_h and Z_{dr}

Outputs:
D_m, N_w and R

Gridded data set:
1x1 km
3 minute

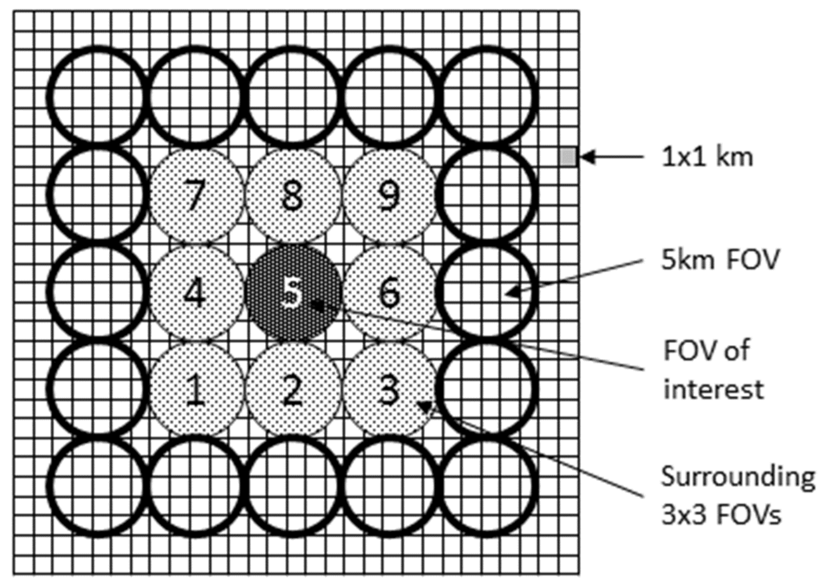
Simulate Ku/Ka-band Measurements

- **Input**: DSD parameters (N_w, D_m, μ) at each 1x1 km
- **Model**: NASA GPM T-matrix scattering tables (Liang Liao)
- **Output**: Simulated 13/35 GHz (Ku/Ka-band) at 1x1 km:
  - Intrinsic reflectivity: $Z(Ku)$ & $Z(Ka)$ (no atten) [dBZ]
  - specific attenuation: $k(Ku)$ & $k(Ka)$ [dB/km]



Simulating Satellite Field-of-View

- TRMM and GPM antenna beamwidths at Earth's surface are 5 km diameter
- Simulate radar field-of-view (FOV)
  - Use Gaussian weighting with 6 dB loss at 5 km
  - Input: 1x1 km resolution
  - Output: 5x5 km resolution
- With each FOV, calculate:
  - Mean value
  - Standard deviation
  - Coefficient of variation
    - ***cov = standard deviation/mean***
- Quantities:
  - R: Rain rate
  - Z(Ku): Ku-band reflectivity
  - k(Ku): Ku-band specific attenuation



Example of Simulated 5 km FOV

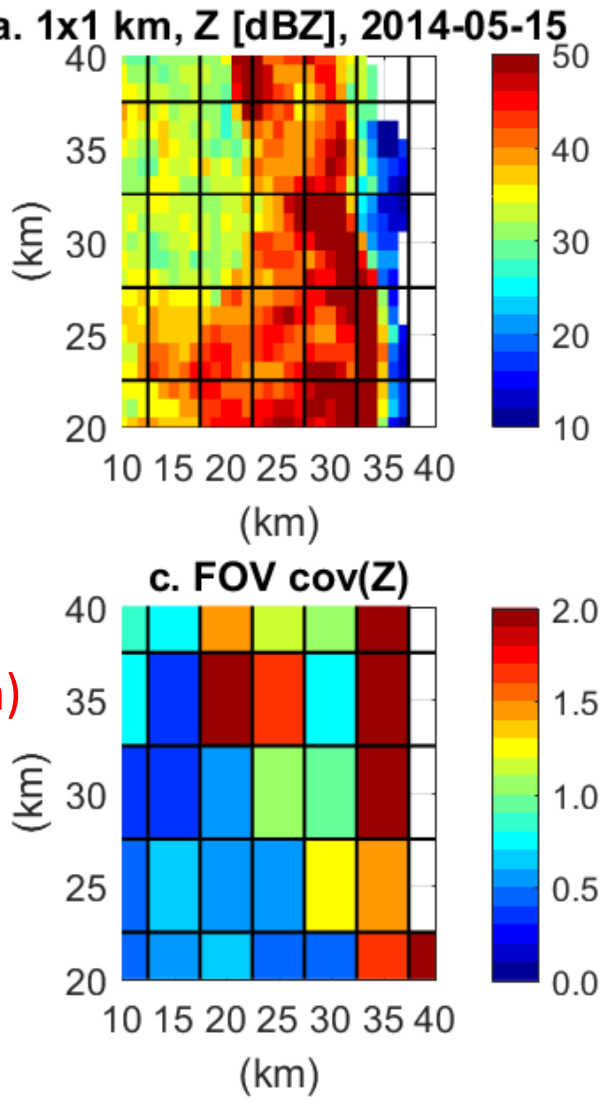
Calculate FOV mean value and sub-FOV variability

Input:
1x1 km

Output:
FOV mean

Output:
FOV cov
(std/mean)

Output:
FOV std



Analyze Rain Filled 3x3 Neighborhoods

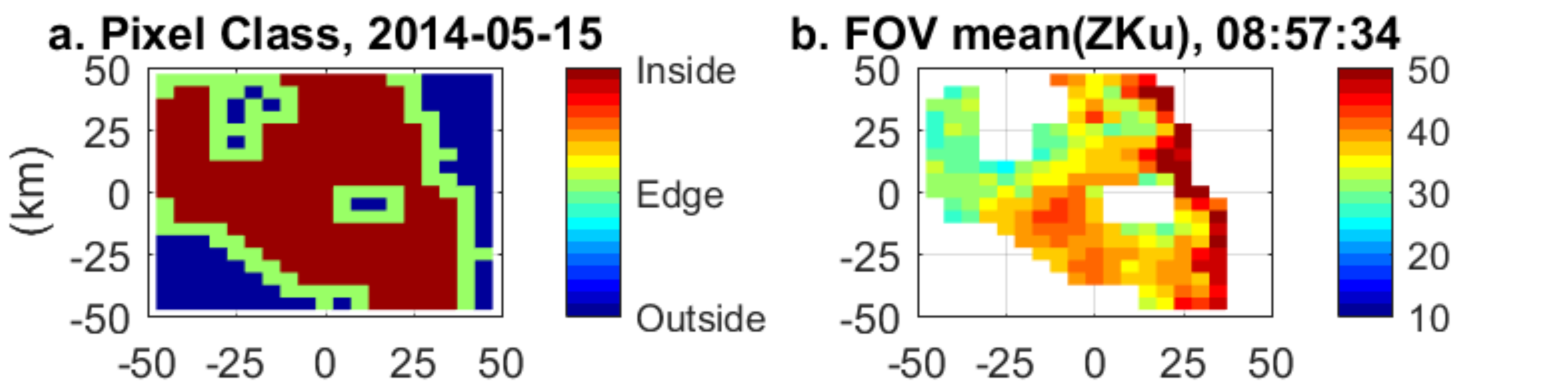
- Want to calculate statistics with only raining pixels
- Each 5x5 km FOV is classified as either:

  Outside FOV: $Z(Ku) < 20$ dBZ no precipitation in FOV

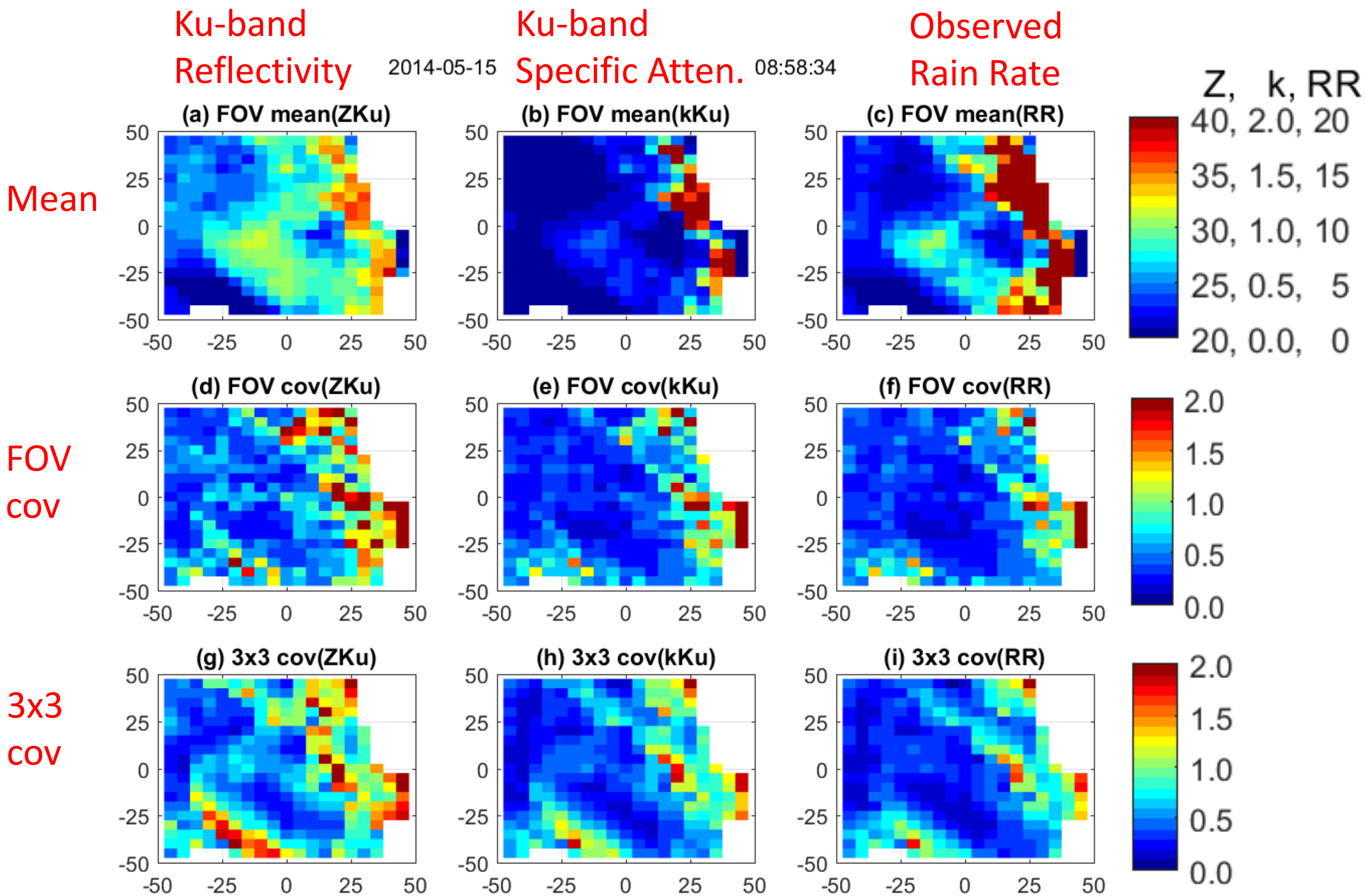
  Edge FOV: $\mathrm{Z(Ku)} \geq 20$ dBZ and at least one neighbor is Outside FOV

  Inside FOV: $\mathrm{Z(Ku)} \geq 20$ dBZ and all 8 neighbors have $Z(Ku) \geq 20$ dBZ

- *Only Inside FOVs are analyzed*



Maps of FOV and 3x3 Estimates



FOV and 3x3 Variability (Individual Scan)

Is there a relationship between 3x3 variability with FOV variability?

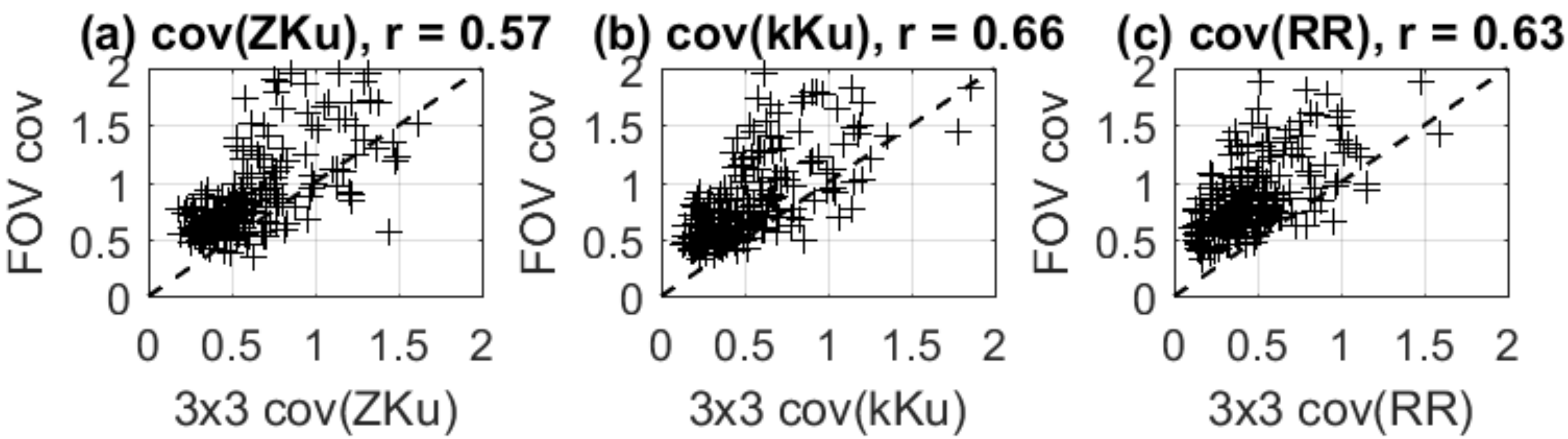
(Downscaling)

- For an individual scan:
  - Scatter plots of FOVcov vs. 3x3cov

Ku-band Reflectivity

Ku-band Specific Atten.

Observed Rain Rate

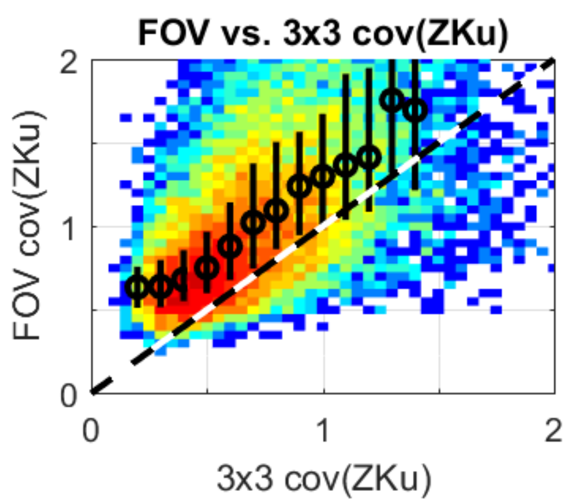


FOV and 3x3 Variability (Storm)

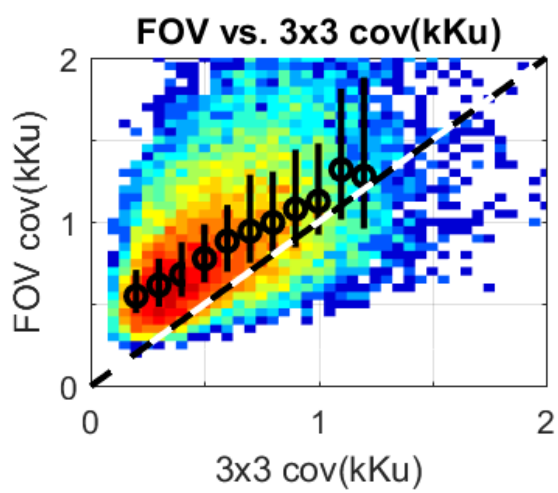
15-May-2014 Storm event

- 12,520 valid 3x3 domains
- Circles: most frequent occurrence
- Vertical lines: 25-to-75 percentiles

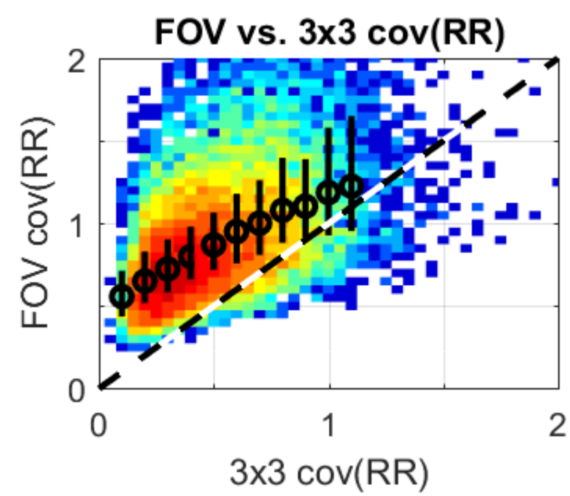
Ku-band
Reflectivity



Ku-band
Specific Atten.



Observed
Rain Rate



Impact of NUBF on Satellite Algorithms

- Impact #1: Area averaging of rain rate and reflectivity
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Magnitude of the inequality increases with spatial variability

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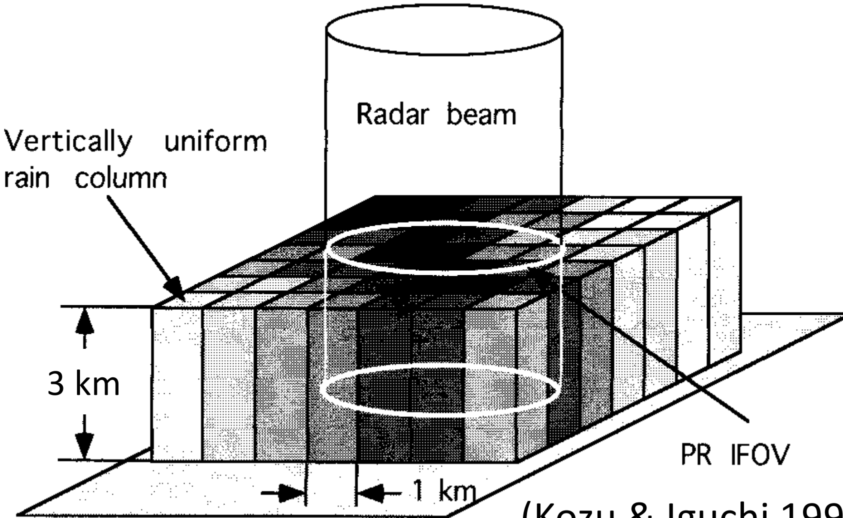
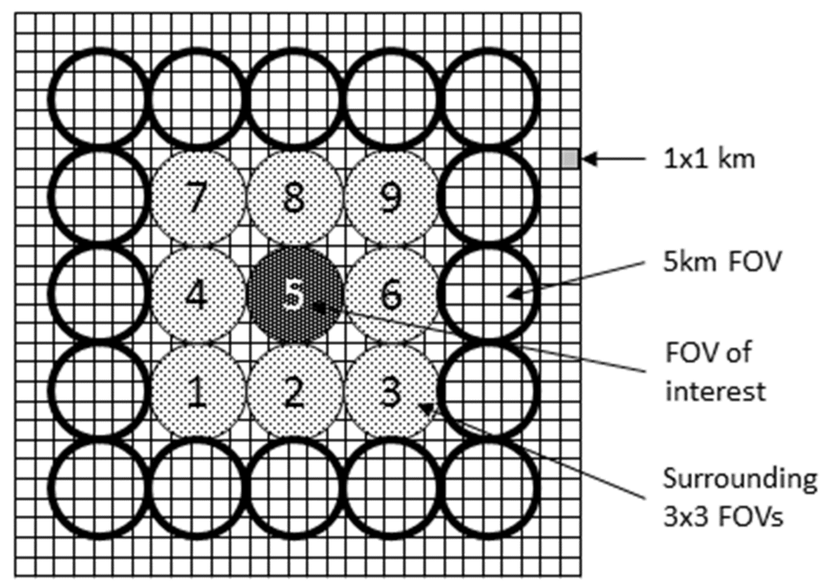
Summary: 3 Scales: 1 km, 5 km & 3x3

- 1x1 km scale:
  - Assume rain is uniform over 1x1 km horizontal scale
  - Construct fundamental k-Z and R-Z power-law relationships
- 5x5 km scale: Field-of-View (FOV)
  - DPR beamwidth at Earth's surface is 5 km
  - Gaussian weighting with 6 dB loss at 5 km
  - With each FOV, calculate:
    - ***Mean value***
    - ***Coefficient of variation cov = std/mean***
- 3x3 Neighboring FOVs
  - 3x3 coefficient of variation



(Kozu & Iguchi 1999)

FIG. 1. Concept of storm model.



1x1 km Data & Horizontal Uniform

- 1x1 km: Determine k-Z, k-R, and R-Z relationships

$k = 0.0242\, R^{1.069}$ (Ku-band) $[k]$ = [dB/km]

$k = 0.2213\, R^{1.024}$ (Ka-band) $[R]$ = [mm/hr]

- 5x5 km: Areal average rain rate

$$< R > = \sum G(\bar{x}) R_{1x1}(\bar{x})$$

where $G(\bar{x})$ is the antenna weighting function

- Assume horizontal uniform rain (no NUBF)

$$< R > = R_{uniform} = R_u$$

$$< k > = k_{uniform} = k_u = c < R >^d$$

$$PIA_{uniform} = (2\, \Delta ht)\, k_u$$ $[PIA]$ = [dB]

where $\Delta ht = 3$ km in this study

PIA Surface Reference Technique (SRT)

- Surface return power is equal to the "clear" return reduced by the precipitation attenuation factor A:

$$\sigma^0_{meas} = \sigma^0_{clear} \sum G(\bar{x}) A(\bar{x})$$ [scaler: $0 \le A \le 1$]

$$= \sigma^0_{clear} \sum G(\bar{x}) 10^{(-0.1)(2\,\Delta ht) k(\bar{x})}$$

[$A = 0$ = extinguished]

[$A = 1$ = no attenuation]

- SRT Attenuation factor:

$$A_{SRT} = \sigma^0_{clear} - \sigma^0_{meas}$$

- SRT PIA [expressed in dB]:

$$PIA_{SRT} = -10log\left(\frac{\sigma^0_{meas}}{\sigma^0_{clear}}\right)$$

$$= 10log\left(\sum G(\bar{x}) 10^{(-0.1)(2\,\Delta ht) k(\bar{x})}\right)$$ [dB]

Rain Rate from Measured PIA

- The measured PIA_{SRT} could contain NUBF:

$$PIA_{SRT,non-uniform} = PIA_{SRT,nu}$$

- Assume $PIA_{SRT,nu}$ is "correct", then rain rate is:

$$PIA_{SRT,nu} = (2\,\Delta ht)k_{nu} \quad \rightarrow \quad k_{nu} = \frac{PIA_{SRT,nu}}{(2\,\Delta ht)}$$

$$R_{nu} = \left[\frac{k_{nu}}{c}\right]^{\frac{1}{d}}$$

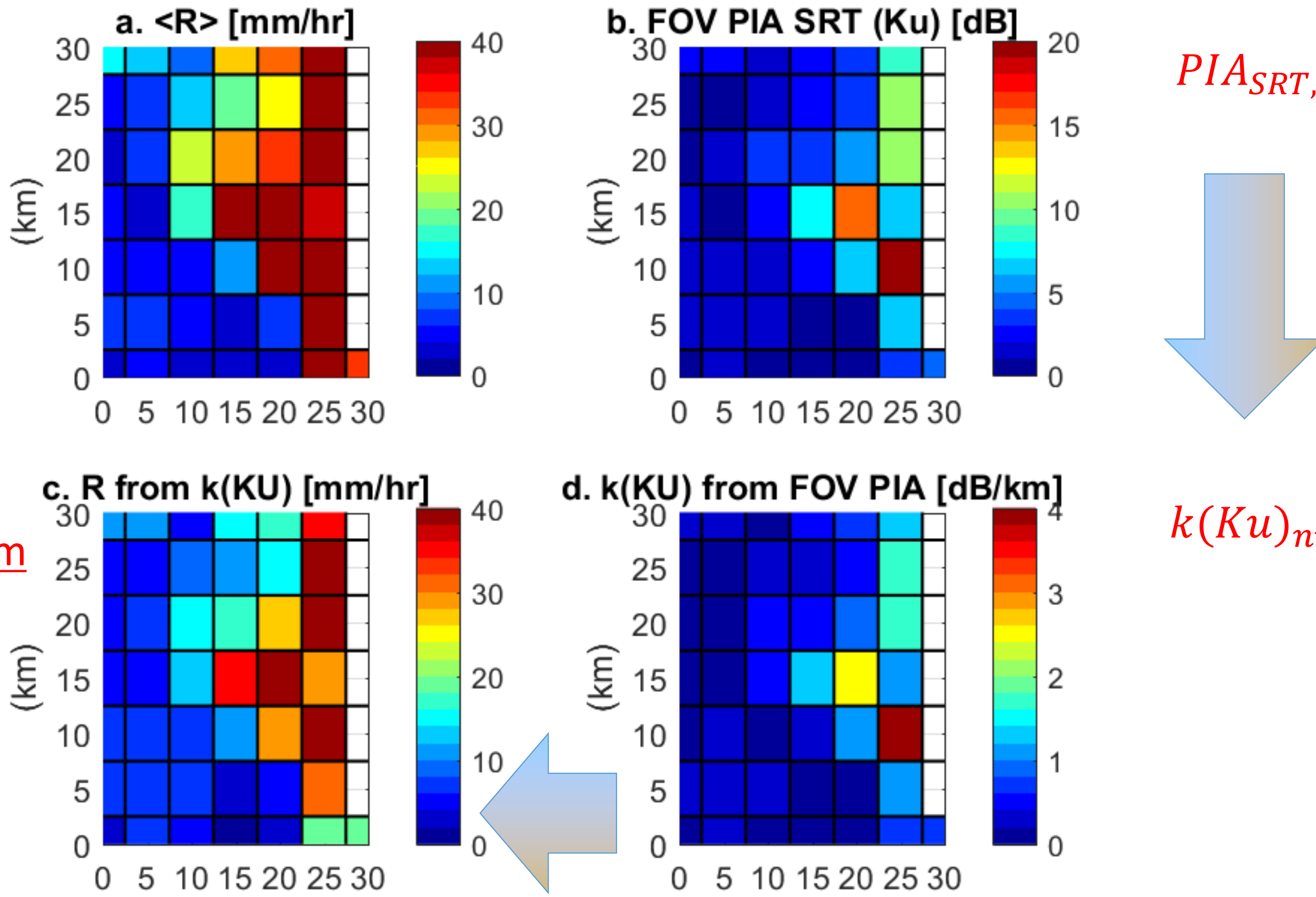
Rain Rate at FOV Resolution

Method #1 (uniform)

Method #2 (non-uniform)

Areal Average uniform R_u

$PIA_{SRT,nu}$

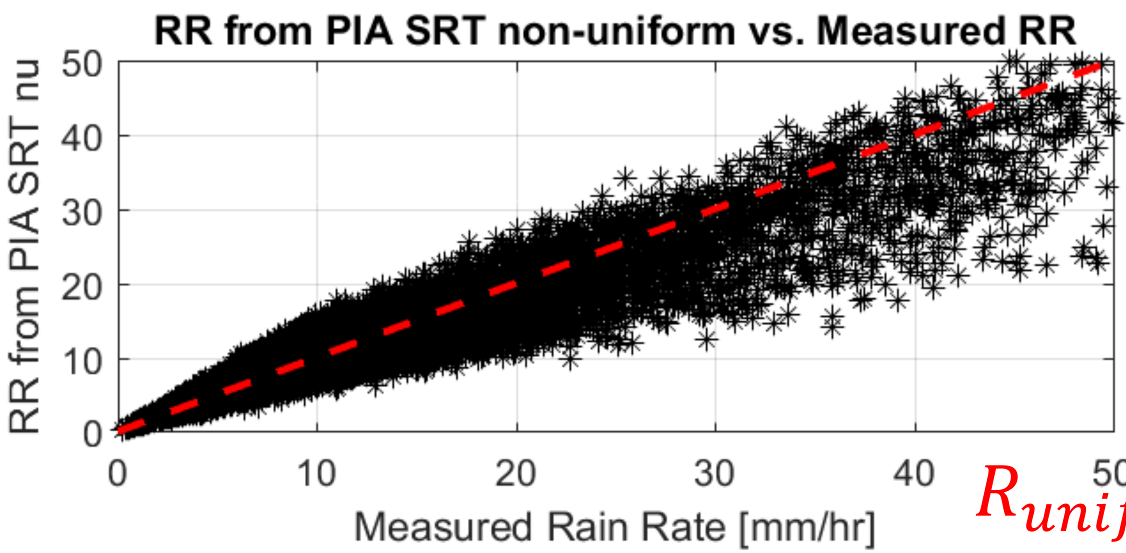


Rain rate non-uniform R_{nu}

$k(Ku)_{nu}$

Rain Rate at FOV Resolution

$\frac{\text{non-uniform}}{R_{nu}}$

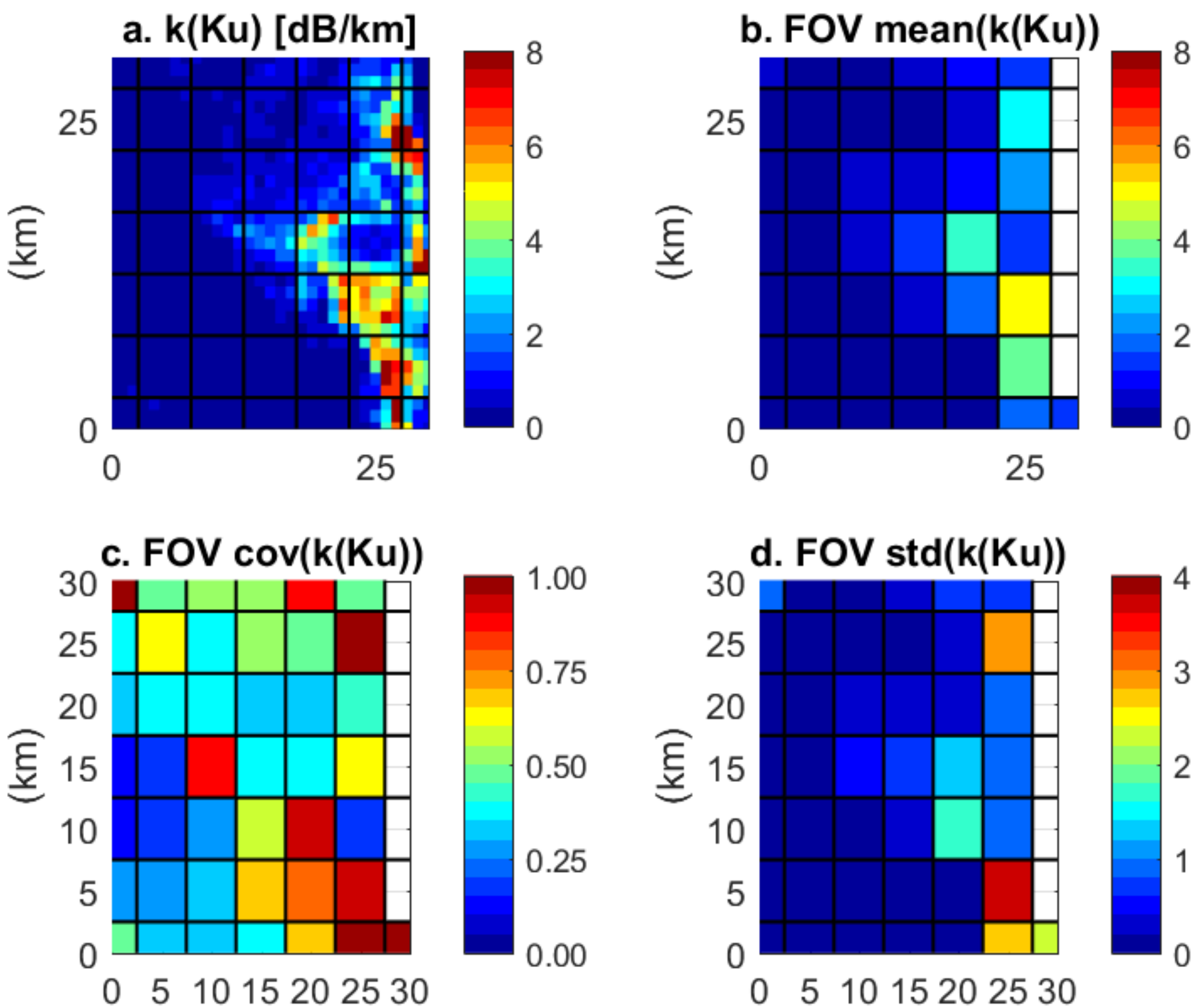


$R_{uniform}$

Specific Attenuation at FOV Resolution

1x1 km

mean

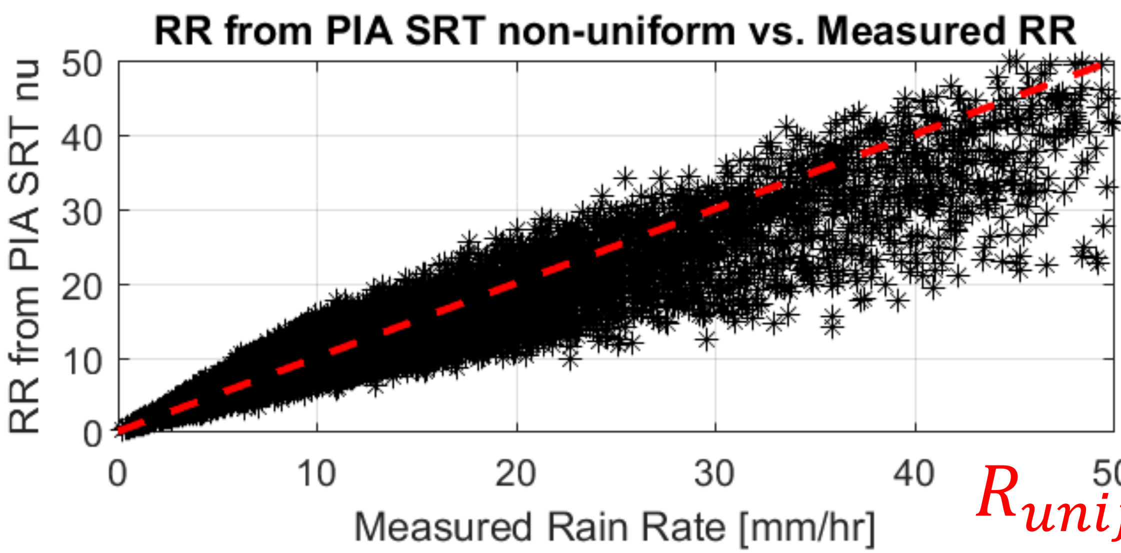


cov

std

Rain Rate at FOV Resolution

$\frac{\text{non-uniform}}{R_{nu}}$



$R_{uniform}$

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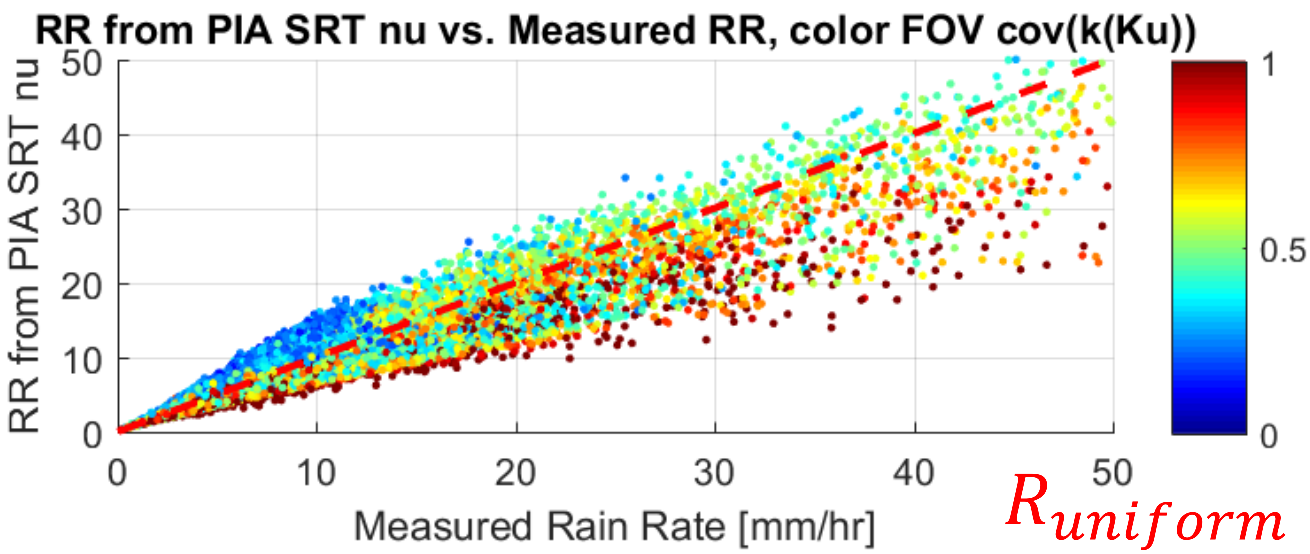


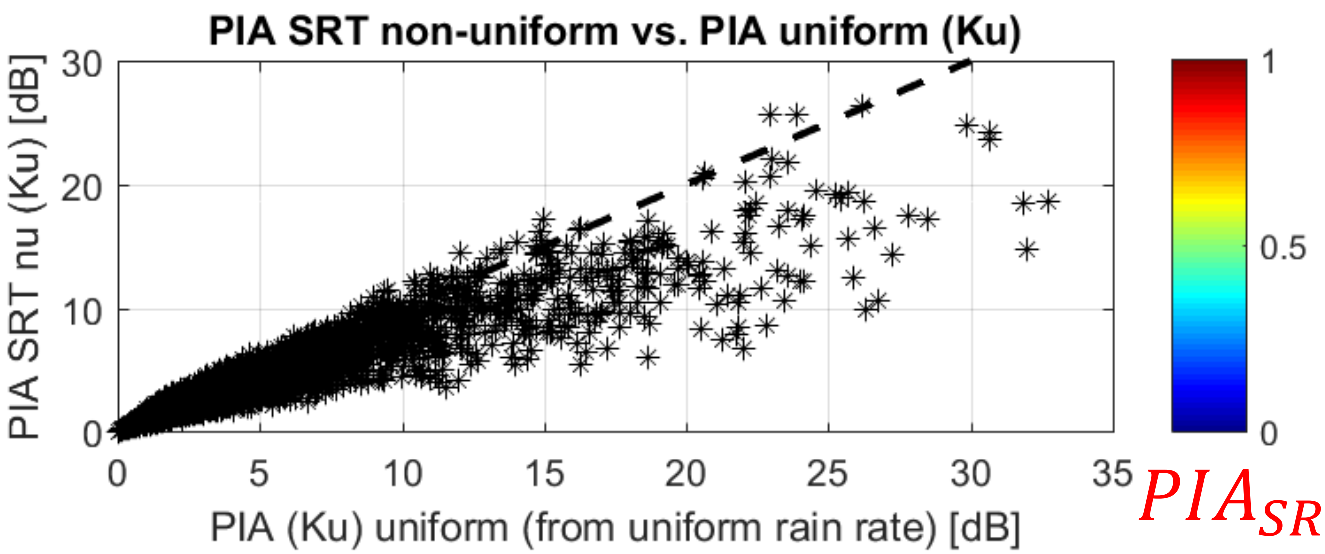
$R_{uniform}$

Color is FOV cov(k(Ku))

k(Ku) variability within 5 km FOV

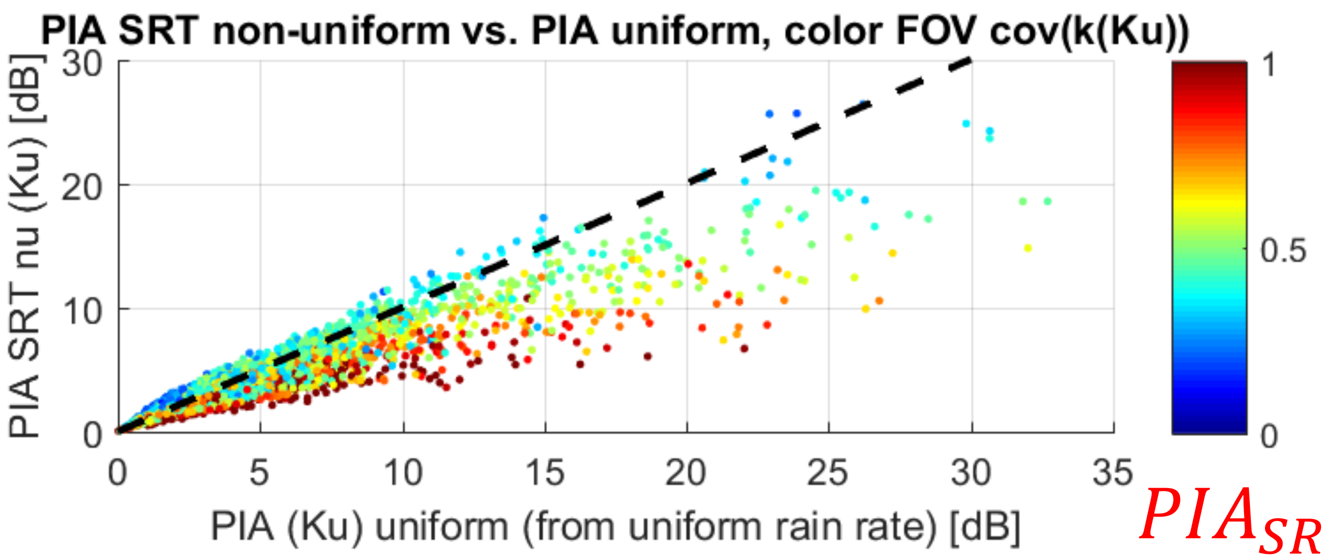
PIA SRT Impacted by FOV variability

non-uniform
$PIA_{SRT,nu}$



$PIA_{SRT,uniform}$

non-uniform
$PIA_{SRT,nu}$



Color is FOV cov(k(Ku))

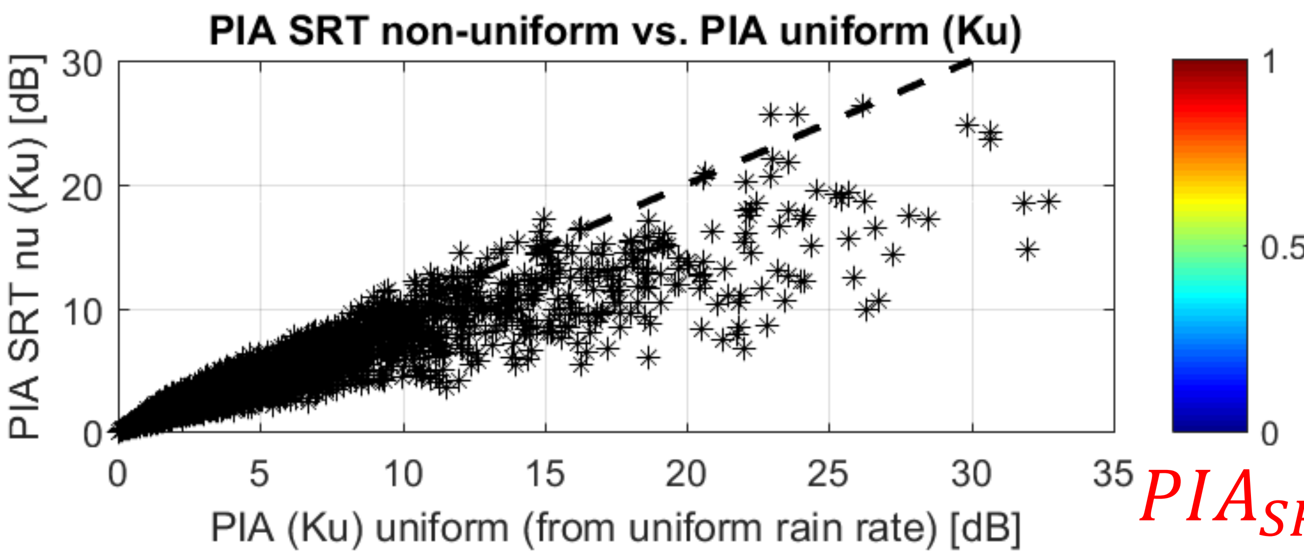
k(Ku) variability within 5 km FOV

$PIA_{SRT,uniform}$

PIA SRT Impacted by 3x3 variability

non-uniform

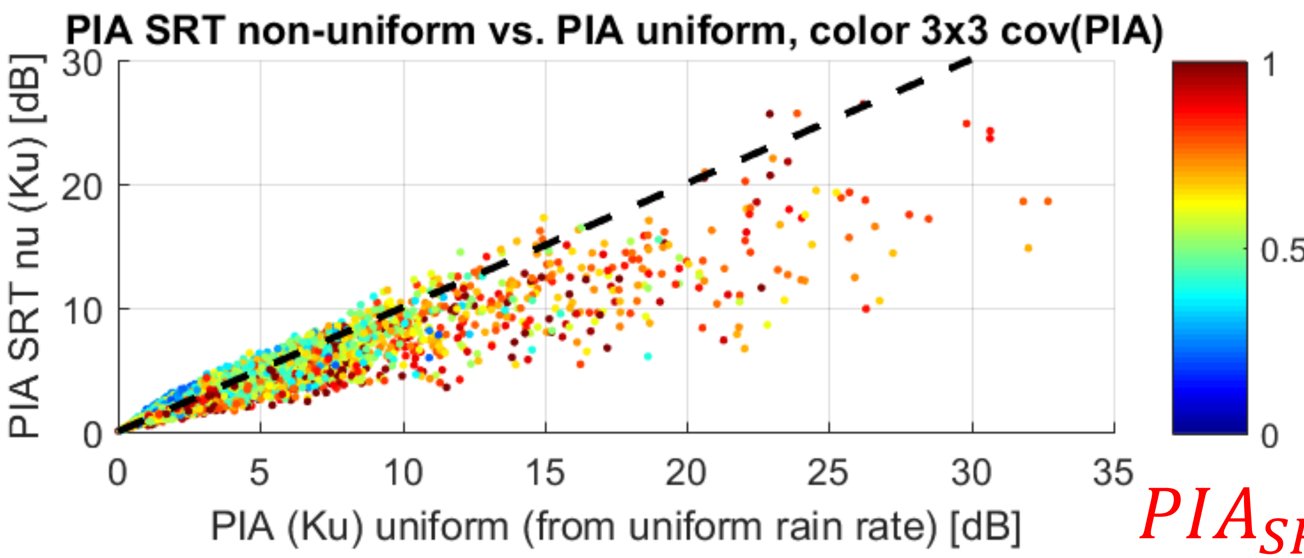
$PIA_{SRT,nu}$



$PIA_{SRT,uniform}$

non-uniform

$PIA_{SRT,nu}$



Color is 3x3 cov(PIA))

PIA variability within 3x3 neighborhood

$PIA_{SRT,uniform}$

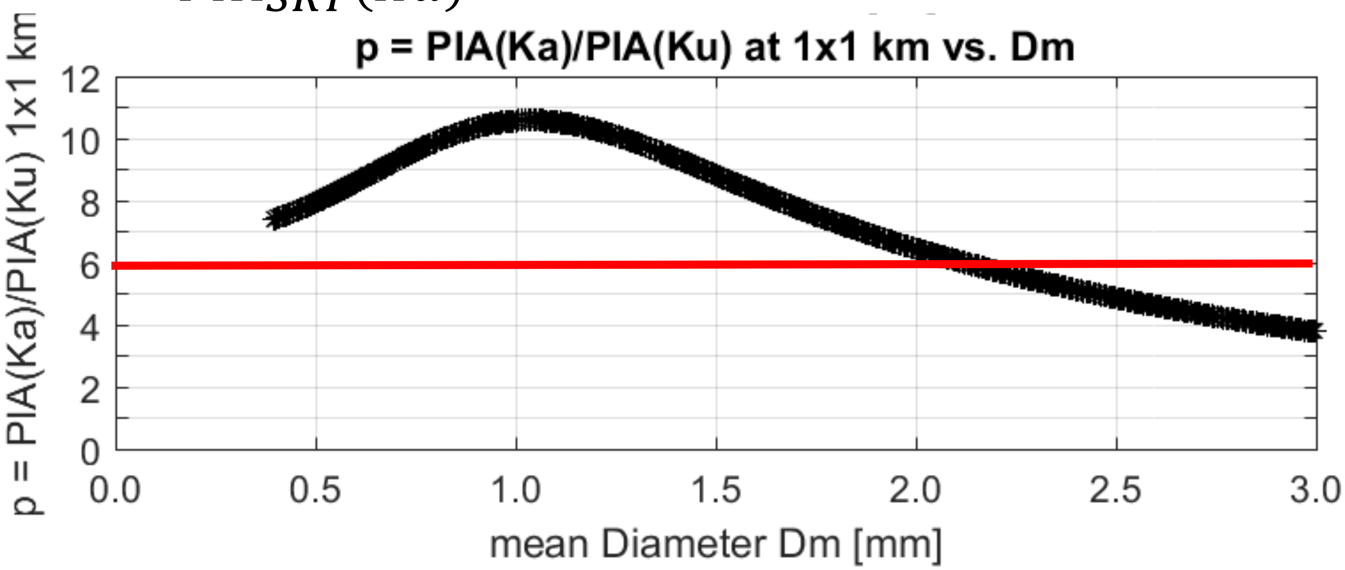
Dual-Frequency PIA SRT

Can we use dual-frequency PIA_{SRT} to infer sub-FOV variability?

Ratio of PIA_{SRT}: $\quad p = \frac{PIA_{SRT}(Ka)}{PIA_{SRT}(Ku)}$

For uniform FOV and DSD parameters (not power-laws):

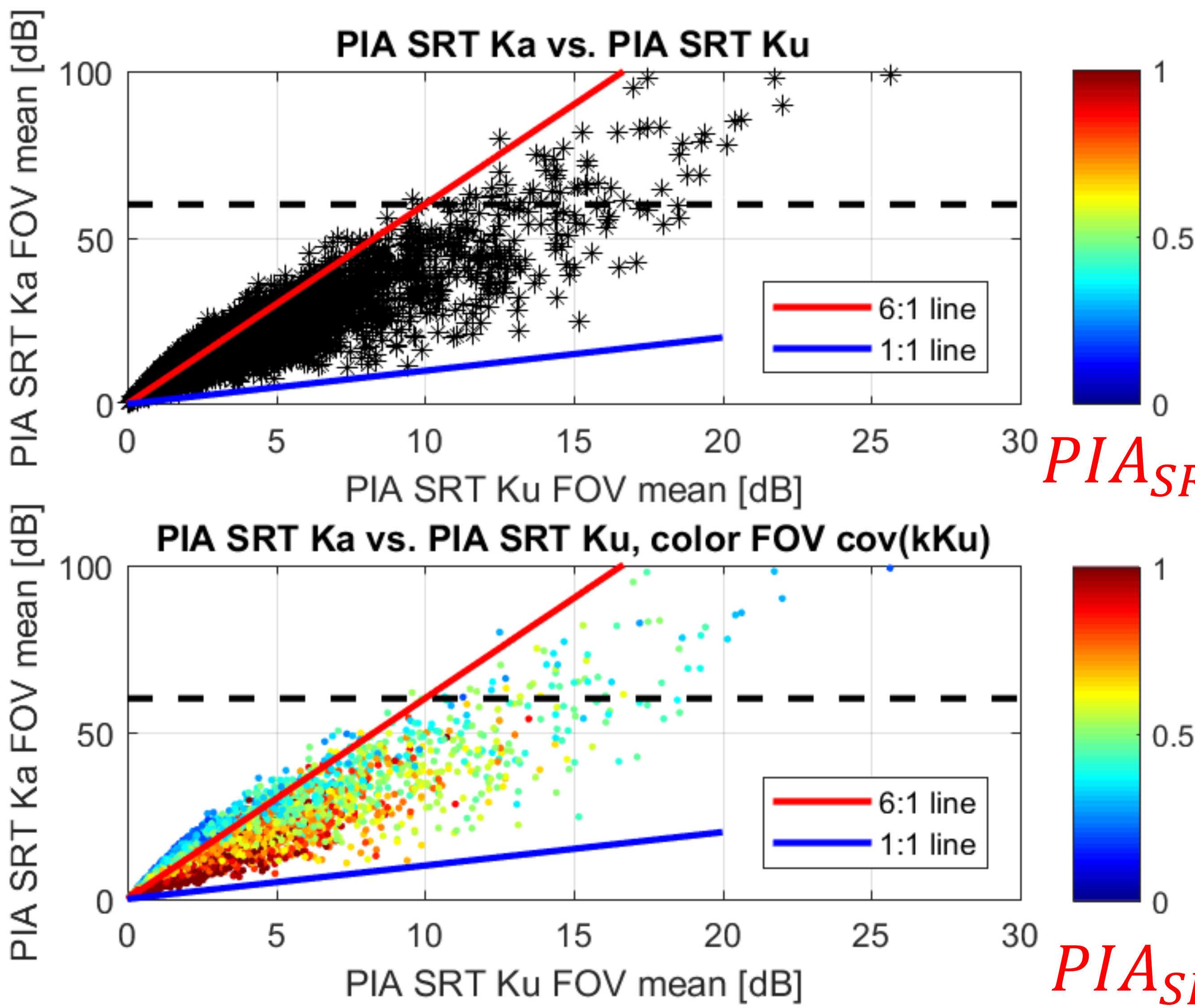
$$p = \frac{PIA_{SRT}(Ka)}{PIA_{SRT}(Ku)} = f(D_m, \sigma_m)$$



$p \sim 6$ for ratio of power-laws

PIA (Ka) vs. PIA (Ku)

PIA_{SRT} (Ka)



$PIA_{SRT}(Ku)$

Color is FOV cov(k(Ku))

k(Ku) variability within 5 km FOV

PIA_{SRT} (Ka)

$PIA_{SRT}(Ku)$

Concluding Remarks and Future Work

Summary of conclusions

- Sub-FOV variability linearly related 3x3 FOV variability
- Correlation was only approximately 0.6
- NUBF parameter could be used as a *statistical constraint* in a probabilistic algorithm, but not in *deterministic algorithms*
- Actual performance depends on algorithm logic and cost minimization procedure

Future Work

- Investigate deviation from expected (uniform FOV) dual-frequency PIA ratio as NUBF variability parameter